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Simplified finite element modelling of end cover separation in RC beams flexurally-strengthened with bonded FRP reinforcement

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Publication Details

Zhang, S. S. & Teng, J. G. (2013). Simplified finite element modelling of end cover separation in RC beams flexurally-strengthened with bonded FRP reinforcement. In R. Al-mahaidi, S. T. Smith, Y. Bai & X. Zhao (Eds.), *Proceedings of the 4th Asia-Pacific Conference on FRP in Structures (APFIS 2013)* (pp. 1-7). Victoria, Australia: Swinburne University of Technology.

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Abstract

The flexural performance of RC beams can be improved using externally bonded (EB) or near-surface mounted (NSM) fibre-reinforced polymer (FRP) reinforcement. One of the commonly observed failure modes of such FRP-strengthened RC beams is the end cover separation failure mode which involves the detachment of the bonded FRP reinforcement together with the cover concrete along the level of the longitudinal steel reinforcement. This paper presents a simplified finite element (FE) model for end cover separation failure in RC beams flexurally-strengthened with either EB or NSM FRP. In this simplified FE model, only the part of the RC beam between the two cracks near the critical end of the FRP reinforcement is simulated. This model leads to the determination of the FRP debonding strain at the cracked section in the strengthened region nearest to the critical end (excluding the one at the end), which can then be used to determine the moment acting on the section at debonding failure through conventional section analysis. The validity of the proposed FE model is verified using laboratory test results.

Disciplines

Engineering | Science and Technology Studies

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SIMPLIFIED FINITE ELEMENT MODELLING OF END COVER SEPARATION IN RC BEAMS FLEXURALLY-STRENGTHENED WITH BONDED FRP REINFORCEMENT

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ABSTRACT

The flexural performance of RC beams can be improved using externally bonded (EB) or near-surface mounted (NSM) fibre-reinforced polymer (FRP) reinforcement. One of the commonly observed failure modes of such FRP-strengthened RC beams is the end cover separation failure mode which involves the detachment of the bonded FRP reinforcement together with the cover concrete along the level of the longitudinal steel reinforcement. This paper presents a simplified finite element (FE) model for end cover separation failure in RC beams flexurally-strengthened with either EB or NSM FRP. In this simplified FE model, only the part of the RC beam between the two cracks near the critical end of the FRP reinforcement is simulated. This model leads to the determination of the FRP debonding strain at the cracked section in the strengthened region nearest to the critical end (excluding the one at the end), which can then be used to determine the moment acting on the section at debonding failure through conventional section analysis. The validity of the proposed FE model is verified using laboratory test results.

KEYWORDS

FRP, strengthening, RC beams, finite element (FE) analysis, cover separation

INTRODUCTION

The use of externally bonded (EB) fibre-reinforced polymer (FRP) reinforcement for the strengthening RC beams in flexure has become increasingly popular over the past two decades. Such beams often fail by debonding which separates the bonded FRP plate from the RC beam (Teng and Chen 2009). The term “debonding” here is used as a generic term to refer to all failure modes where the composite action between the FRP plate and the RC beam is not maintained. Two types of debonding failures have been observed: (1) end debonding in which debonding initiates near an end of the FRP plate and propagates towards the strengthened region of the beam; and (2) intermediate crack (IC) debonding in which debonding initiates at a major flexural crack and propagates towards an end of the FRP plate. End debonding failures can be further separated into two main modes: (a) end cover separation which involves the detachment of the bonded FRP plate together the cover concrete along the level of the longitudinal steel reinforcement (Teng and Chen 2009), as shown in Figure 1a; (b) end interfacial debonding which involves debonding in the concrete adjacent to the adhesive layer (Teng and Chen 2009). End cover separation, whose failure process is initiated by the formation of a crack near the critical end of the FRP plate, followed by the propagation of a major crack at the level of the tension steel reinforcement towards the middle of the strengthened region, is much more common than end interfacial debonding such FRP-strengthened RC beams. The latter mode may only happen when the FRP plate width is much smaller than the beam width so that the plate-to-beam plane is weaker than the plane between the tension steel bars and the concrete.

In recent years, the near-surface mounted (NSM) FRP strengthening method has attracted significant attention worldwide as one of the promising new techniques for structural strengthening and as an effective alternative to the EB FRP strengthening method. The NSM FRP technique involves the cutting of grooves in the cover concrete and the embedding of FRP bars in the grooves using an adhesive (normally an epoxy adhesive). In RC beams flexurally-strengthened using NSM FRP, several debonding failure modes have been observed in laboratory tests (Zhang and Yu 2013). Of these debonding failure modes, end cover separation which is similar to that observed in RC beams strengthened with EB FRP has also been found to be one of the main failure modes (Figure 1b).

While laboratory tests are still indispensable in studies on debonding failures in FRP-strengthened RC beams, finite element analysis, once verified, offers an effective complementary tool for understanding the mechanism

of failure and for generating numerical data for the development of simple strength models. This paper presents a simplified FE model for end cover separation failure in RC beams strengthened in flexure with EB or NSM FRP based on findings gained using a more sophisticated 2-D nonlinear FE model proposed by Zhang and Teng (2010) for such FRP-strengthened RC beams. In this simplified FE model, only the segment of the RC beam between the two cracks near the critical end of the bonded FRP reinforcement is included. The tensile and shear behaviour of the concrete, the bond behaviour between FRP and concrete as well as that between steel and concrete, are all properly considered in the simplified FE model. Furthermore, the important radial forces exerted by the tension steel bars on the surrounding concrete are also accounted for in this FE model. For this FE model, whether EB FRP or NSM FRP is used in strengthening leads mainly to differences in modelling the bond-slip response between FRP and concrete, so the two strengthening methods can be both treated in the same FE model. This simplified FE model offers a good understanding of the debonding failure mechanism and can be used a parametric study to generate numerical results for use in the formulation of simple strength model for use in design.

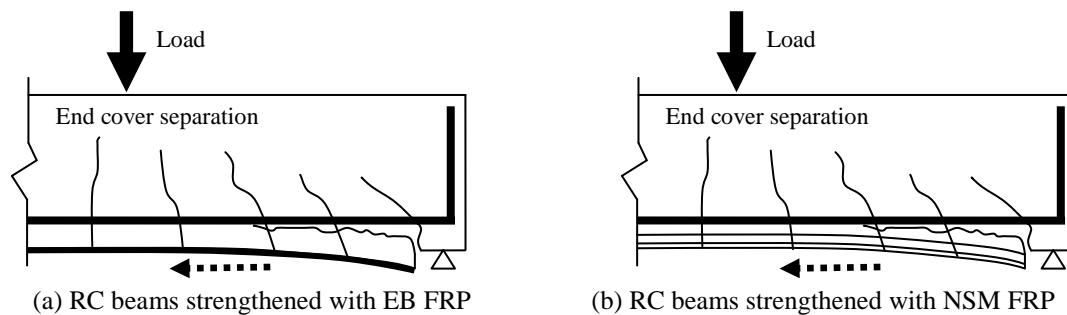


Figure 1 End cover separation

EXISTING STUDIES

A review of the existing work on the FE modelling of RC beams strengthened with EB FRP shows that a well-accepted FE model, which closely captures the failure mechanism and facilitates a relatively simple analysis, had not been developed for end cover separation before the authors' recent work (Zhang and Teng 2010): none of the previous studies included accurate modelling of cracked concrete (particularly with regard to the shear behaviour) or the bond-slip behaviour between steel and concrete. The modelling of the FRP-to-concrete bond-slip behaviour had also been inadequate although this aspect is believed to be less critical to the accurate prediction of end cover separation. In some of the previous studies, clear evidence for the correct prediction of the plate-end cover separation failure mode was not available (Arduini et al. 1997; Rahimi and Hutchinson 2001). Furthermore, Yang et al.'s (2003) model required time-consuming and complicated re-meshing while Camata et al.'s (2007) model was not truly predictive as the experimentally-observed crack pattern needed to be known before the FE model could give good predictions.

For RC beams strengthened with EB or NSM FRP, the present authors study (Zhang and Teng 2010) recently proposed a nonlinear FE 2D continuum (plane stress) model for predicting end cover separation failure. In this 2-D nonlinear FE model, aspects which may be important for accurate predictions are all carefully considered: the tensile and shear behaviour of cracked concrete, the bond-slip relationship between steel and concrete as well as that between FRP and concrete, the critical plane between cover concrete and the tension steel bars, and most importantly, the radial stresses exerted by the tension steel bars onto the surrounding concrete. The last factor was, for the first time, shown to be an important factor for the accurate modelling of end cover separation failure. The findings of that study (Zhang and Teng 2010) formed the basis of the present study.

SIMPLIFIED FE MODEL

General

Although the 2D nonlinear FE model proposed by Zhang and Teng (2010) can provide accurate predictions of end cover separation of FRP-strengthened RC beams in flexure, it is a rather involved model and is not convenient for parametric studies to establish a strength model for use in design. Therefore, a simpler model capable of similarly accurate predictions is desirable. Such a model is presented in the remainder of this section.

Simplifications

In an end cover separation failure, an inclined crack usually occurs near the critical end of the FRP plate/bar, and another crack (referred to as the left crack hereafter with reference to Figure 2) usually appears in the strengthened region at a certain distance (i.e. the crack spacing) away from the plate/bar end, as illustrated in Figure 2. Obviously, if the strain in the FRP reinforcement at the left crack at end cover separation is known, the moment acting on the corresponding section can be easily found through section analysis if the plane section assumption is still adopted; the ultimate load can then be easily calculated. Therefore, the segment of the RC beam between the two cracks near the critical end of the FRP reinforcement can be isolated to form a simplified model for FE analysis (Figure 2), with the moments on the two cracked sections being realized through external loads (R , P_1 , P_2 and P_3 in Figure 2). Through FE analysis using the simplified model, the FRP strain at cover separation failure at the left cracked section (i.e. Point A in Figure 2) can be obtained.

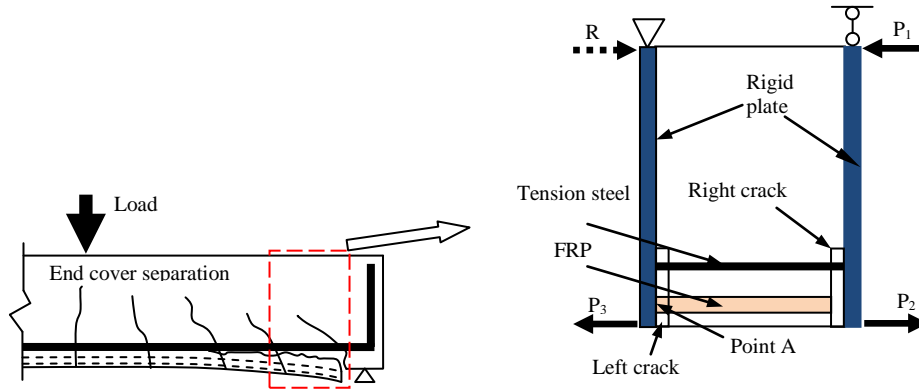


Figure 2 Simplified FE model

A rigid plate is attached to each cracked section to impose the plane section assumption. The plane section assumption may not be exactly valid here, but it can simplify the modelling process and may not introduce substantial errors. Both horizontal and vertical restraints are imposed on the top end of the left rigid plate, and a vertical restraint is applied on the top end of the right rigid plate. The load P_1 in the horizontal direction acts at the top end of the right rigid plate, the load P_2 ($P_2 = -P_1$) acts at the bottom end of the right rigid plate, and the load P_3 acts at the bottom end of the left rigid plate. Based on equilibrium, the reaction force R at the top end of the left rigid plate is always equal to P_3 in magnitude but opposite in direction. The ratio between the moments on the two cracked sections can be achieved by specifying appropriate load ratios (i.e. $|P_1/P_3|$ or $|P_2/P_3|$).

Choice of elements

The concrete is modelled using 4-node plane stress elements, and some concrete near the bottom part of the rigid plate on each side is removed to represent the two adjacent cracks. As the loading increases, the initial cracks may propagate vertically or along an inclined direction, depending on the moment ratio between the two cracked sections. The steel reinforcement is simulated using 2-node beam elements, and both end of the steel reinforcement are connected to the rigid plates. The thickness of the concrete at the steel reinforcement level is adjusted to remove the area occupied by the steel reinforcement. The FRP is also modelled using 2-node beam elements. Only one end (the left end in Figure 2) of the FRP strip/bar is connected to the adjacent rigid plate, while the other end (the right end) representing the actual strip/bar end is left free. An EB FRP plate is positioned at the bottom surface of the beam while an NSM FRP bar is positioned at the mid-height of the groove.

Cohesive-element-pair

Zhang and Teng (2010) suggested for the first time ever that the radial stresses (i.e. τ_r in Figure 3) exerted by the tension steel bars onto the surrounding concrete play an important role in a cover separation failure. In the present simplified FE model, the cohesive-element-pair (CEP) devised by Zhang and Teng (2010) is employed to account for these radial stresses.

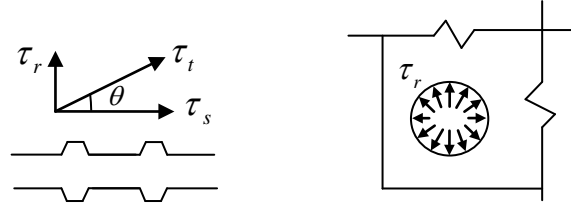


Figure 3. Bond stresses between steel and concrete

As shown in Figure 4, the CEP consists of two 4-node cohesive elements each of which connects two nodes of the plane stress element representing the adjacent concrete to the two nodes of the beam element representing the steel reinforcement located at the mid-height of the concrete element. The upper cohesive element is employed to simulate the shear bond behaviour between the tension steel bars and the surrounding concrete, while the lower cohesive element simulates the interaction between the tension steel bars and the concrete in the normal (vertical) direction. Before any deformation occurs, the CEP overlaps with the adjacent concrete element whose height is equal to the diameter of the tension steel bars. When slips between the tension steel bars and the surrounding concrete occur, the upper cohesive element will deform in shear to represent the shear bond-slip behaviour and does not experience any deformation in the normal direction. In the meantime, from the shear bond force developed in the upper cohesive element, the associated normal (vertical) bond force in the lower cohesive element can be deduced; the lower cohesive element does not possess any shear stiffness or strength.

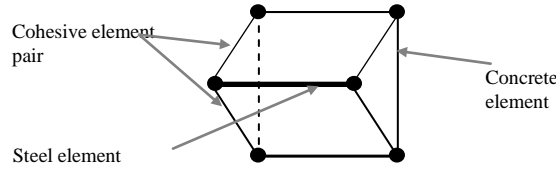


Figure 4. Cohesive-element-pair (CEP)

Modelling of materials

For concrete, the yield surface of Buyukozturk (Buyukozturk 1977) with the associated flow rule is used to describe the compression-dominated behaviour, with the equivalent stress-plastic strain behaviour being defined by the uniaxial compressive stress-strain curve for concrete proposed by Elwi and Murray (1979). The maximum tensile stress criterion is employed to describe the initiation of cracking. The cracking behaviour of concrete is modelled using the orthogonal fixed smeared crack model with the crack band concept; an exponential tension-softening curve is used following Hordijk's (1991) model, in which the tensile strength and the tensile fracture energy of the concrete are determined based on (CEB-FIP 1993). Therefore, the failure surface is a combination of the failure surface of the Buyukozturk plasticity model (Buyukozturk 1977) and the maximum tensile stress criterion. The shear stress-crack slip model proposed by Okamura and Maekawa (1991) was adopted to describe the shear behaviour of the cracked concrete. For steel bars, an elastic-plastic stress-strain relationship is assumed. The FRP strip is modelled as an isotropic linear-elastic material with brittle behaviour in tension.

Modelling of interfaces

For the bond behaviour between steel and concrete, the bond-slip model proposed by (CEB-FIP 1993) is adopted. For beams strengthened with EB FRP, the simplified version of Lu et al.'s (2005) bond-slip model for FRP-to-concrete interfaces is used. For beams strengthened with NSM FRP, the bond-slip relationship proposed by Zhang et al. (2013) is used. The angle θ between the radial stress and the shear bond stress (Figure 3) is taken to be 30 degrees, following Zhang and Teng (2010). Assuming that the radial stress and the shear bond stress are distributed uniformly around the circumference of a steel bar, then the internal force generated by the steel rebar in the vertical direction per unit length can be calculated as

$$f_r = D \tau_r = D \tau_s \tan \theta \quad (1)$$

where D is the diameter of the steel bar.

VERIFICATION OF THE PROPOSED FE MODEL

Usually, the failure strain in the FRP reinforcement at the left cracked section (i.e. Point A in Figure 2) when end cover separation occurs is not recorded during a laboratory test. In fact, it is difficult to capture this failure strain

in a test because the positions of flexural cracks are not known in advance. Therefore, the validity of the proposed FE model cannot be verified directly through comparisons of the FRP failure strain at the left cracked section. A comparison of the moment at the left cracked section is made instead below by assuming that the moment and the FRP strain at the left cracked section can be related by a conventional section analysis.

It should be noted that the beam segment length included in the simplified FE model is the same as the crack spacing, so the crack spacing may have a significant effect on the FRP failure strain. Although some empirical formulas are available for calculating the crack spacing, the large differences among these formulas may cause excessive errors to the predicted failure strain in the FRP reinforcement. Based on the above consideration, in the present study, only test results of beams which satisfy the following criterion are used for comparison with FE predictions: the picture of the beam at failure was provided, and the crack pattern was clear enough so that the crack spacing could be directly measured from the picture. Only five test specimens [Beam AF4 tested by Ahmed et al. (2001); Beam 3 by Maalej and Bian (2001); Beam 3B by Smith and Teng (2003); Beam CS-C10-B by Yao and Teng (2007); and Beam NSM-s2 by Barros et al. (2007)] were found to meet this criterion.

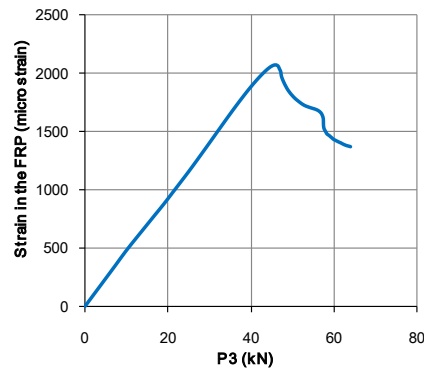


Figure 5. FRP strain at the left cracked section versus load P_3 for specimen AF4 (Ahmed et al. 2001)

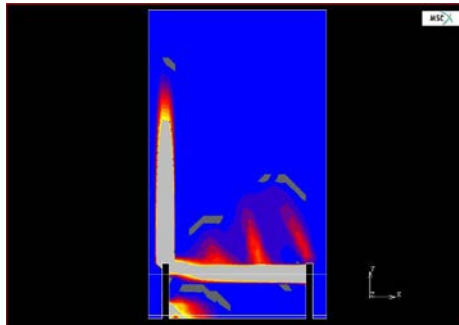


Figure 6. Predicted failure mode of specimen AF4 (Ahmed et al. 2001)

The FE study began with a convergence study for Beam AF4 tested by Ahmed et al. (2001). Three element sizes were examined: 20mm, 10mm and 5mm. From the convergence study, it was found that negligible differences were caused by the different element sizes in terms of load-deflection curves, indicating that the FE results were not sensitive to element sizes within such a reasonable range. The element size of 10 mm was then selected for use in the FE analyses of all the other specimens, considering that it led to accurate load-deflection curves and clear crack patterns, without the computing time becoming excessive. The curve of FRP strain (at the left cracked section) versus load (P_3) and the failure mode of specimen AF4 (Ahmed et al. 2001), obtained with the simplified FE model, are shown in Figure 5 and Figure 6 respectively.

For the section analysis used in the present study, the BS 8110 (1997) compressive stress-strain curve of concrete was adopted. The maximum compressive strain in the concrete was assumed to be 0.0035. The measured crack spacing, the predicted FRP failure strain, and the test and predicted shear forces at failure for each of the five selected specimens are given in Table 1. It can be seen that with the use of the measured crack spacing, the simplified FE model can predict the failure shear force very closely; the average of the prediction-to-test load ratios is 1.034, with a standard deviation (STD) of 0.111, and a coefficient of variation (CoV) of 0.107.

Table 1. Verification of the proposed FE model

Source	Specimen	Measured crack spacing (mm)	Failure strain from the simplified FE model ($\mu\epsilon$)	Shear force from test (kN)	Shear force from FE analysis (kN)	FE Prediction / Test
Ahmed et al. (2001)	AF4	90	2065.2	55.5	57.5	1.036
Maalej and Bian (2001)	3	130	1913.2	43	37.4	0.870
Smith and Teng (2003)	3B	70	1001.9	65.3	66.1	1.012
Yao and Teng (2007)	CS-C10-B	90	1233.3	66.3	77.9	1.174
Barros et al. (2007)	NSM-s2	105	4253.8	46.7	50.2	1.076
Statistical characteristics	Average =					1.034
	STD =					0.111
	CoV =					0.107

CONCLUSIONS

A simplified 2-D continuum FE model for end cover separation failure of FRP-strengthened RC beams, which includes only the segment of the RC beam between the two cracks near the critical end of the bonded FRP reinforcement, has been presented in the paper. The bond behaviour between FRP and concrete and that between steel and concrete are properly represented, leading to accurate predictions of the propagations of flexural and shear cracks. Most importantly, the radial stresses exerted by the longitudinal steel bars onto the surrounding concrete are taken into account following Zhang and Teng (2010). This simplified 2-D FE provides a simple but effective approach to investigate the end-cover separation failure mode in FRP-strengthened RC beams and can be used to conduct parametric studies to develop strength models for end cover separation failure.

ACKNOWLEDGMENTS

The authors are grateful for the financial support received from the National Basic Research Program of China (973 Program) (Project No.: 2012CB026201), the National Natural Science Foundation of China (Project No. 51308483) and The Hong Kong Polytechnic University. The authors would like to thank Prof Jian-Fei Chen in Queen's University Belfast for his helpful comments.

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